Interim Report and Preliminary Assessment of GE GeoSpring Heat Pump Water Heater

12 July 2011

Prepared for
Bonneville Power Administration
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Contract Number 44717

Interim Report and Preliminary Assessment of GE GeoSpring Heat Pump Water Heater

Residential Heat Pump Water Heater Evaluation Project

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Revision 2

Revision History

Rev #	Date	Details of Change	Reason
0	2-18-2011		First release
1	4-27-2011	Revised Table 2 and discussion on 1st hr and EF rating explaining both "simple" EF and DOE method EF calc.	Corrected error in 1st rating. Completed full DOE method EF calculation for 24hr test.
2	7-11-2011	a) Added section on Draw Profile and capacity b) Updated observations section to include bullets and revised conclusions in regarding tank storage capacity and efficiency.	a) More data analyzed since first report release b) Harmonized layout with the two other HPWH reports and clarified role of tank storage capacity and heating output capacity.

Introduction

Using the measurement and verification (M&V) plan developed by Ecotope to assess heat pump water heaters (HPWH), the GE GeoSpring was evaluated at the National Renewable Energy Lab. The M&V plan consists of a series of tests to assess equipment performance under a wide range of operating conditions. The tests include measurement of basic characteristics and performance including first hour rating and DOE Energy Factor (EF), description of operating modes, measurement of heat pump system efficiency and the effects of restricted airflow. For a detailed description of the tests and conditions, refer to the M&V plan document.

The report is intended as a "first look" at the results and, as such, should still be considered a preliminary assessment. A final assessment will be prepared and delivered later and will include two more HPWH models. This report focuses on the equipment performance itself and not on the interactions with the building in which it is installed.

Basic Equipment Characteristics

The GE GeoSpring, model # GEH50DNSRSA, is an all electric water heater consisting of a heat pump integrated with a hot water tank. The equipment has two methods of heating water:

(1) by using a heat pump to extract energy from the ambient air and transferring it to the water, or

(2) by using resistance heating elements immersed within the tank.

The heat pump compressor and evaporator are located on top of the tank. Two variable speed, axial fans draw ambient air from the sides at the upper section of the unit across the evaporator coils, and exhaust colder air out the back. The condenser coil, which transfers heat to the water, is wrapped around the outside of the tank.

The lab conducted a set of measurements which provide the information a design professional would reference on a basic equipment specification. These measurements are given in Table 1 and discussed below. For comparison purposes, the table also shows the values given by GE's equipment specification. To a large extent these values agree.

Like a traditional, electric tank water heater, the GeoSpring has an upper and lower resistance heating element. Each element uses 4.5kW (with a 240V supply) when activated but they are interlocked so only one may operate at a time. Traditionally, the upper element turns on first and, because of its placement, is able to heat the upper layer of the tank. When the upper tank temperature reaches the setpoint, the lower element turns on to heat the remaining portion of the tank.

The compressor in the GE HPWH is also interlocked with the resistance elements so only one of the three heating components is active at any given time. This means the maximum power draw of the equipment is limited to 4.5kW. Lab measurements show the compressor draws 300-700W depending on both tank water and ambient air temperatures. Compressor power use increases both with increasing water and air temperatures. Other power consuming components on the equipment are the fan which varies from 5-10W depending on conditions and the control circuit which uses 3W constantly.

The GeoSpring HPWH is marketed and sold as having 50 gallon capacity but careful measurements showed the unit in the lab held 45.5 gallons. National guidelines on the sizing of equipment allow a 10% variation in nominal versus actual size. This water heater fits within those guidelines albeit on the lower end. It should be noted that the difference in nominal size vs actual size is not unique to HPWHs and occurs with traditional electric resistance tanks as well.

Table 1. Basic Characteristics for GE GeoSpring HPWH

	Laboratory Measurement	Manufacturer's Specification
Power		
Upper* Element (kW)	4.5	
Lower* Element (kW)	4.5	
Compressor** (W)	300-700	550, 700
Standby (W)	3	2
Fan*** (W)	5-10	---
Airflow Path	Inlet on sides. Exhaust to back.	
Airflow (cfm)	100-175	---
Refrigerant	R-134a	
*elements interlocked. 240V supply		
**range depends on water T and ambient T. Power increases with both. Spec sheet lists 550W while the nameplate data on the equipment lists 700W.		
***variable speed depends on conditions		

Operating Modes and Sequence of Heating Firing

The HPWH has an integrated circuit control board which may be programmed in a number of ways to control when the heating components, compressor or resistance elements turn on and off. GE has developed several control strategies, referred to as "operating modes" to determine equipment operation. The GE HPWH has four basic modes of operation from which the user may select. They are, in order of most efficient to least efficient:

- "eHeat" – compressor only, unless evaporator coil frosting occurs
- "hybrid" – combination of compressor and resistance elements
- "high demand" – combination of compressor and resistance elements favoring the elements
- "electric only" – resistance heat elements only

The M&V plan called for a set of tests to explore the control strategies for the water heater modes of operation. Each test began with the water heaters full of water at set point. A draw was initiated and continued until the compressor turned on (if possible for that mode of operation). The draw was then stopped and the unit was allowed to recover. A second draw was performed for the same air conditions and set point. This second draw was allowed to continue until the electric heaters came on or until 40 gallons of water had been drawn. The units were then allowed to recover. This same procedure was followed for air at 47°F dry bulb, 67°F dry bulb, and 95°F dry bulb, but only the hybrid modes of operation (for the GE, this included Hybrid and High Demand modes) were tested at 95°F and 47°F air.

The following observations were made during the operating mode tests.

Start up: When the GE is turned on in eHeat or Hybrid mode, the fan will immediately turn on; the compressor will turn on in 2-3 minutes.

The GE uses its compressor, upper element, and lower element separately. Each of the electric elements is sized at 4.5kW, and the GE is programmed such that the elements are not allowed to operate simultaneously or with the compressor.

eHeat Mode: When operating in eHeat mode, the compressor is the only heat source in almost all conditions. The compressor is the first heating component to turn on once a draw is initiated and is exclusively used to recover the tank. During the tests, even when the water outlet temperature fell to 77°F, the resistance elements did not turn on. The coldest two air conditions (47°F and 57°F) caused some icing on the coils at the beginning of the COP test, when the water was coldest. One of the electric heaters came on after 30 minutes of compressor operation if there was a threat of icing. There was no measured high temperature limit for the GE operating in eHeat mode.

Hybrid Mode: In hybrid mode, the compressor is used unless demand is too high, in which case the resistance elements are used. When a draw is initiated, the compressor will turn on first. If less than 30 gallons is drawn, the compressor will stay on to achieve set-point temperature. If greater than 30 gallons is drawn, the upper element will come on. Once the set-point is reached at the top of the tank, the upper element will turn off and the lower element will turn on. Lastly, when operating in hybrid mode, if a water draw is large enough to force the resistance heaters to come on, the water heater will not attempt to use the compressor again for the rest of that recovery cycle.

High Demand Mode: In the lab evaluation, there was no discernable difference in operation between the hybrid and high demand modes. Presumably, the manufacturer has optimized the controls for high demand mode to activate the resistance heaters sooner than in hybrid mode but this was not observed likely due to the size and type of draws carried out in the lab.

Electric Only Resistance Mode: When a draw is initiated, the lower element turns on and if the draw is stopped, will remain on until the tank reaches its set-point. If the draw is continued, the lower element will turn off and the upper element will turn on. Once the top of the tank reaches the set-point temperature, the upper element turns off and the lower element turns on.

First Hour Rating and Energy Factor

To rank the comparative performance of heat pump water heaters the Department of Energy has established two tests. The first produces a first hour rating which determines how much useable hot water the heater makes in one hour. The second, a 24-hr simulated use test, produces an energy factor (EF) which relates how much input energy is needed to generate the 64.3 gallons of hot water used in the simulated 24 hour period. For tank-type water heaters, the first hour rating depends largely on tank volume and heating output capacity. The energy factor depends on the heating system efficiency and the heat loss rate of the tank. The normative performance characteristics of the equipment are shown in Table 2 and discussed in the rest of this section. Importantly, although the lab carried out the tests in alignment with the DOE specification, the outputs here should not be considered official ratings – those are the ones reported by the manufacturer.

Table 2. Performance Characteristics for GE GeoSpring HPWH

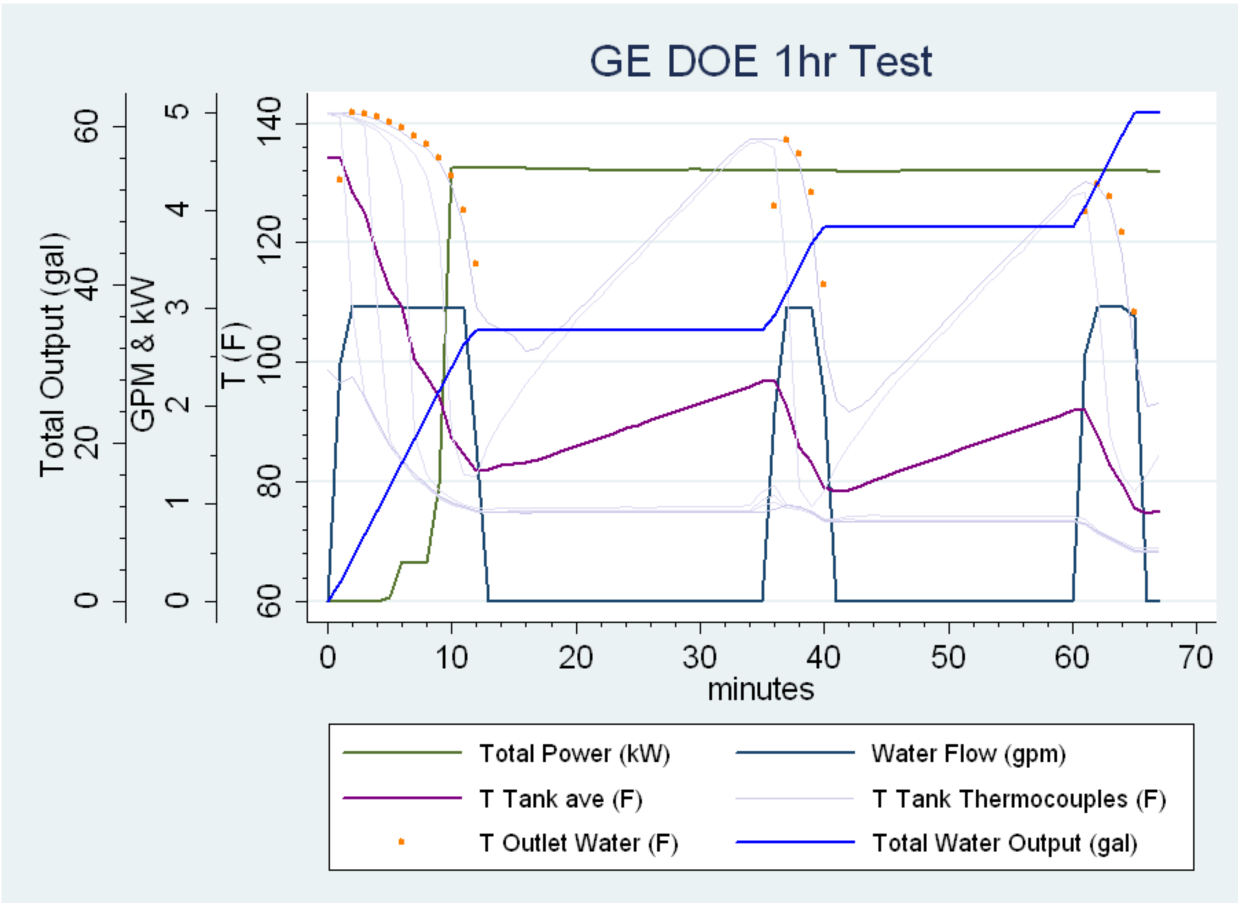
	Laboratory Measurement	Manufacturer's Specification
Tank Volume (gal)	45.5	50
First Hr Rating (gal)	57	63
Energy Factor (hybrid mode) DOE method calc	2.41	2.35
Energy Factor (hybrid mode) simple calc	2.37	
Tank Heat Loss Rate (Btu/hr°F)	3.8	---

The lab conducted both the 1-hr and 24-hr tests to demonstrate repeatability with the manufacturer's data. The tests are conducted in "hybrid" mode which is the default setting on the equipment when shipped by GE. Both tests were conducted per the DOE specification. The tank temperature set point was 140°F which resulted in a starting average tank temperature of 135.3°F essentially matching the standardized 135°F ±5°F starting requirement. The energy factor (EF) calculations show good agreement with the published specification sheet and actually show slightly improved performance. In contrast, the first hour rating diverges from the spec sheet showing a lower value.

The data from the one hour test are plotted in Figure 1. Approximately five minutes into the first draw, the HPWH compressor turns on (green line showing about 400W). As the tank temperature falls further, the upper resistance element turns on (green line to 4.5kW) to satisfy the increasing demand. One of the two resistance elements will stay on for the remainder of the test. Even under the most optimized ambient conditions, the resistance heat element of this water heater will provide more capacity than the heat pump compressor. Therefore, to maximize output (at the expense of efficiency), the resistance elements are favored in this test. Interestingly, despite preparing the water heater per the DOE conditioning pre-draws, the tank started in a stratified state with the lowest thermocouple (lowest 1/6 of tank) showing a temperature of 100°F. This stratification at the bottom part of the tank occurs whenever the resistance elements are used to finish heating the tank.

Although the total water drawn during this test was 61.7 gal, when a draw is initiated at the 60 minute of the test, the calculation procedure only allows a portion of that water draw to be counted towards the 1st hr rating. For this test run, approximately 75% of the last draw adds to the total rating volume.

Figure 1. DOE One Hour Test. The dark blue line shows the prescribed water draws at a 3gpm flow rate. The bright blue line shows the cumulative water drawn during the test. The green line plots the total equipment power consumption. The thick purple line displays the average tank temperature while the thin lavender lines show the temperatures reported from the six thermocouples placed at different heights (corresponding to equal volume segments) within the tank. Lastly, the yellow dots plot the output water temperature. Output water temperature is always just slightly warmer than the highest thermocouple inside the tank.



The 24-hr simulated use test consists of six 10.7 gallon draws equally spaced over six hours followed by 18 hours of standby. The standard test conditions are 67.5°F, 50% RH ambient air, 135°F tank set point and 58°F incoming water temperature. As previously mentioned, this test used a 140°F set point but this did result in the starting average tank temperature, 135.3°F essentially matching the test standard starting conditions. As with the first hour rating, the heater operating mode was set to "hybrid." Figure 2a shows the first nine hours of the test so the draw events and recovery can be examined in more detail. Figure 2b shows the full 24 hours which also demonstrates the tank heat loss rate.

At the most basic level, an energy factor is the ratio of total useful energy output to total energy input. In any test, the tank may start and end at different average temperatures (energies) so that must be taken into account in the calculation. In this 24hr test case, as with the 1hr test, the tank begins with a slug of cold water in the bottom 1/6 of the tank. Although the thermostat is satisfied everywhere else in the tank, this brings the average temperature down. The tank ends the test at a higher average temperature because the compressor has been running which transfers heat to the very bottom of the tank.

The Energy Factor (EF) was calculating in two ways: using a “simple” method and the DOE prescribed method. The DOE test method prescribes a standard set of operating conditions to use for the test and for normalization purposes in the calculation of the EF. The “simple” calc divides energy output by energy input and does not normalize to standard conditions. The extent that the simple EF agrees with the DOE method EF, reflects how tightly the lab (and the equipment tested) held to the standard conditions. Both EF calculations are given in Table 2. For comparison to the manufacturer’s data, the DOE method EF should be used. By calculating the EF in two ways, we can demonstrate that the lab held very closely to the test tolerances.

Figure 2a plots much of the same data as Figure 1 but also adds a calculation of the instantaneous coefficient of performance (COP) which is plotted as red dots. The instantaneous COP is a measure of how much heat is added to the hot water in a given time interval divided by the energy used to create or deliver that heat in that interval (in this case one minute). For electric resistance heat, the COP is generally assumed to be 1. In contrast, the COP for heat pumps can vary greatly depending largely on the ambient air conditions (heat source) and the tank temperature (heat sink). More discussion of the COP occurs later. The scatter in the COP plots is due to uneven, short-term fluctuations in the tank temperatures but the general trend is clear. For most of the test, the COP is around 2.5. Only after the last draw, and with full tank recovery, does the COP start to drop to 2.

Figure 2a. DOE 24hr Simulated Use Test. First 9 hours of test.

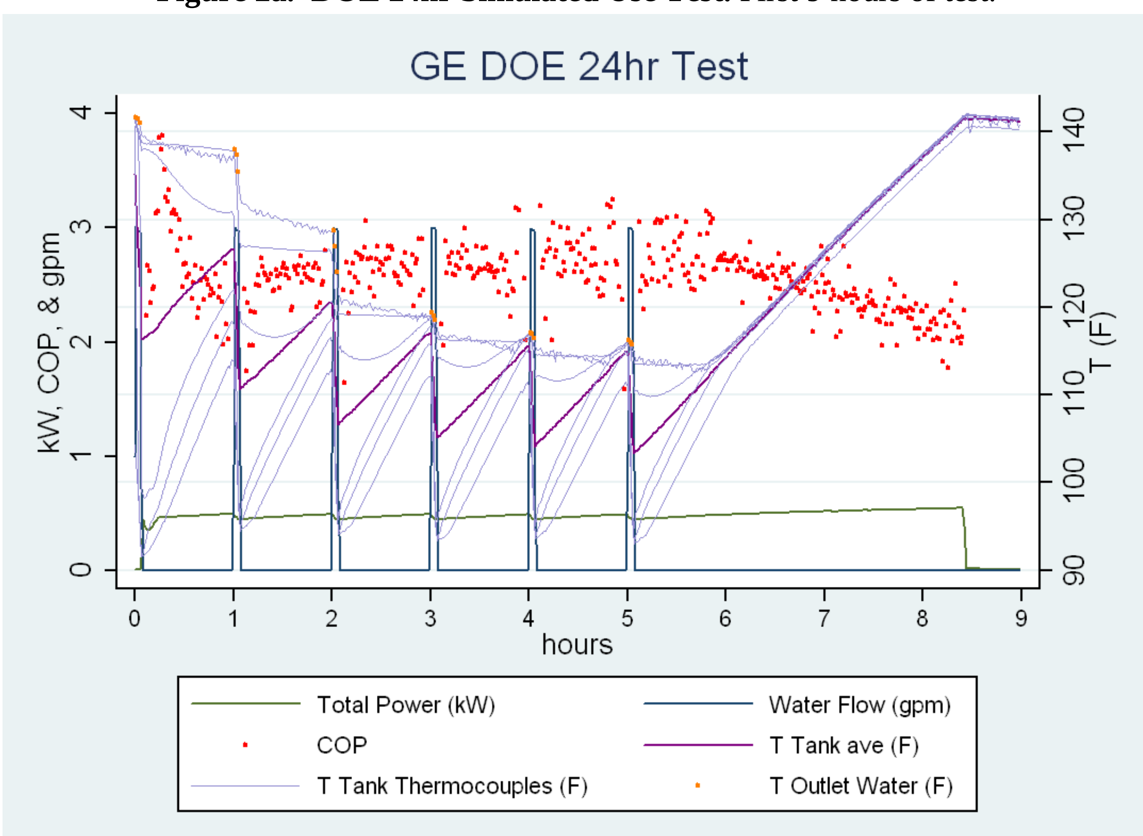
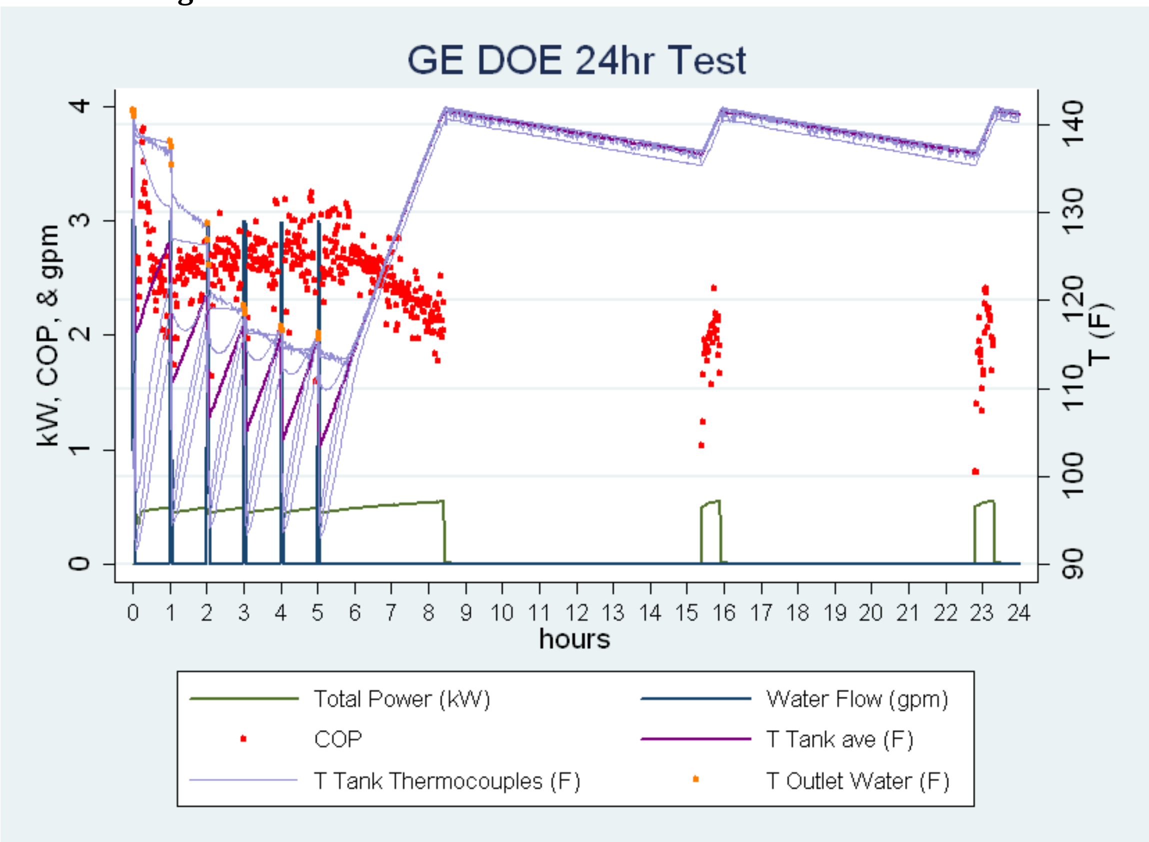


Figure 2b shows the full 24hrs of data. From hour 9 to 15, the tank is in standby mode with the only power draw being 3W for the control circuits. From the change in average water temperature over this period, a heat loss rate of 3.8 Btu/hr°F was calculated for the tank. For a tank installed inside a house with a set point of 120°F, this heat loss amounts to 486 kWh/yr. If installed in a garage with an average year round temperature of 50°F, the losses amount to 680 kWh/yr. Unlike traditional electric tanks which recover the standby loss with a COP of 1, Figure 2b shows the GE HPWH will recover standby losses with a COP of 2 thereby cutting that portion of annual energy use in half.

Figure 2b. DOE 24hr Simulated Use Test. Full 24 hours of test.



A peculiarity of these two tests is that the water heater essentially uses resistance elements exclusively for the one hour rating and the heat pump exclusively for the EF rating. This control strategy is the optimum one for obtaining the highest test results in both categories. It is unclear, however, that these results will translate into direct energy savings in a house. The EF calculated out of the 24hr tests depends precisely on the draw pattern in the simulated use test. Actual hot water use in homes varies greatly from this pattern and the HPWH's controls are likely to respond differently to these draw patterns. For example, if the daily use pattern in a given household triggers the resistance elements, the EF will decrease. Further, in the 24hr test, the outlet water temperature falls 25°F from the first to last draw. Because the DOE test standard specifies a set point of 135°F (140°F in our case), this still results in useable hot water at 110°F (115°F). In contrast, if homes set the temperature to 120°F (which is common for plumbing codes and therefore a common default factory setting), a drop of 25°F from this point will result in output water temperatures below a useable level of 105°F. Therefore, caution should be used when applying the EF to determine actual energy use in houses.

Equipment COP

To fully understand the HPWH performance, the M&V plan called for a mapping of equipment COP at varied tank temperatures and ambient air conditions. These COP measurements reflect how efficiently the heat pump components of the HPWH are operating under any given set of conditions. These COPs do not apply when the resistance elements are operating, in which case the COP is 1. The performance map is extremely useful in understanding how well the equipment will operate in a conditions encountered in garages and unconditioned basements. The test conditions for the COP mapping is given in Table 3.

Table 3. Test conditions for COP Mapping

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water	
	Dry-Bulb		Wet-Bulb						
	F	C	F	C	RH	F	C	F	C
COP-47	47	8	43	6	73%	35	2	135	57
COP-57	57	14	50	10	61%	35	2	135	57
COP-67	67.5	20	57	14	50%	35	2	135	57
COP-77	77	25	61	16	40%	35	2	135	57
COP-85	85	29	68	20	42%	35	2	135	57
COP-95	95	35	75	24	40%	35	2	135	57
COP-95 dry	95	35	66	19	20%	35	2	135	57
COP-105	105	41	84	29	42%	35	2	135	57
COP-105 dry	105	41	69	21	16%	35	2	135	57

Equipment efficiency is dependent on the water temperature in the tank, ambient air temperature, and ambient air moisture content. Figure 3 shows the change in COP with average tank temperature; a decreasing COP for increasing water temperatures for the various tests. The lines in the plots are linear fits to the measured data.

Figure 4 shows the COP dependence on ambient air dry bulb for a set of given tank temperatures. The COP actually depends on both dry bulb and wet bulb temperatures but, for simplicity, the wet bulb dependence is not shown in the plot. The fact that analysis of the test data shows dependence not only on wet bulb but also on dry bulb temperature suggests that the tests measured a difference in latent heat removal at the different testing conditions. Using regression techniques, the performance map was turned into a function so that efficiency can be predicted at any set of conditions.

$$COP = -5.848 - 0.024 \cdot Ttank + 0.012 \cdot Tdb - 0.035 \cdot Twb + 3.096 \cdot \ln(Twb)$$

where Ttank = average tank temperature (F)
Tdb = ambient air dry bulb temperature (F)
Twb = ambient air wet bulb temperature (F)

Further implications of heat pump performance will be explored in later reports.

Figure 3. The plotted lines are fits to measured data.

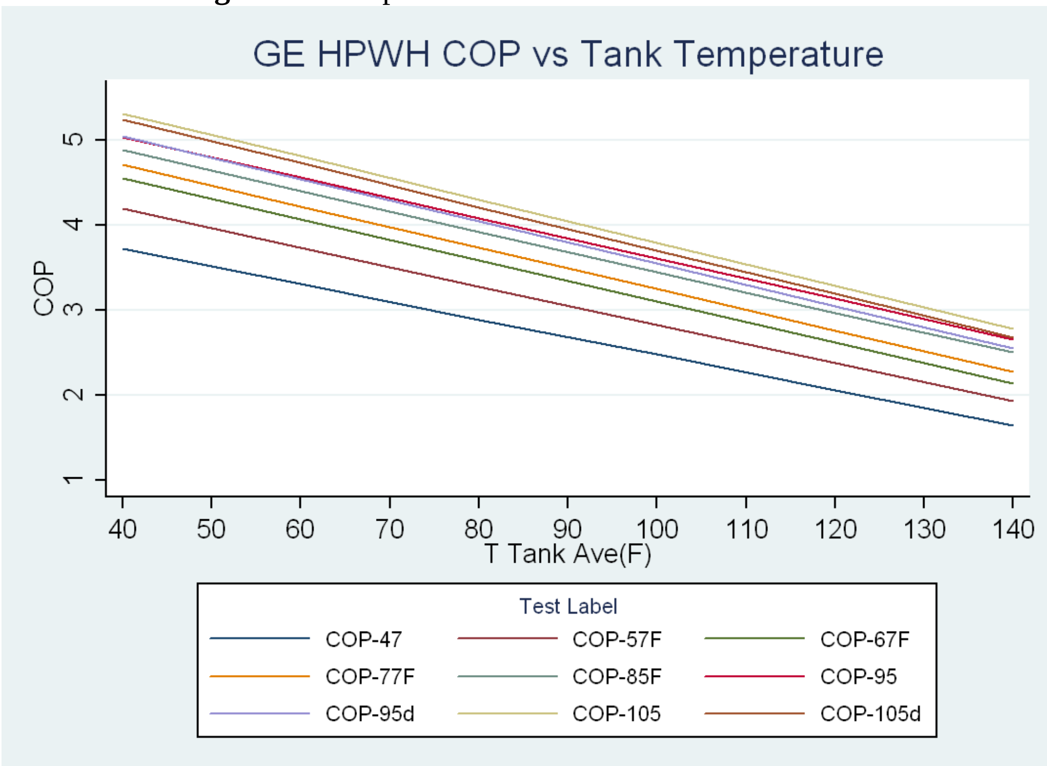
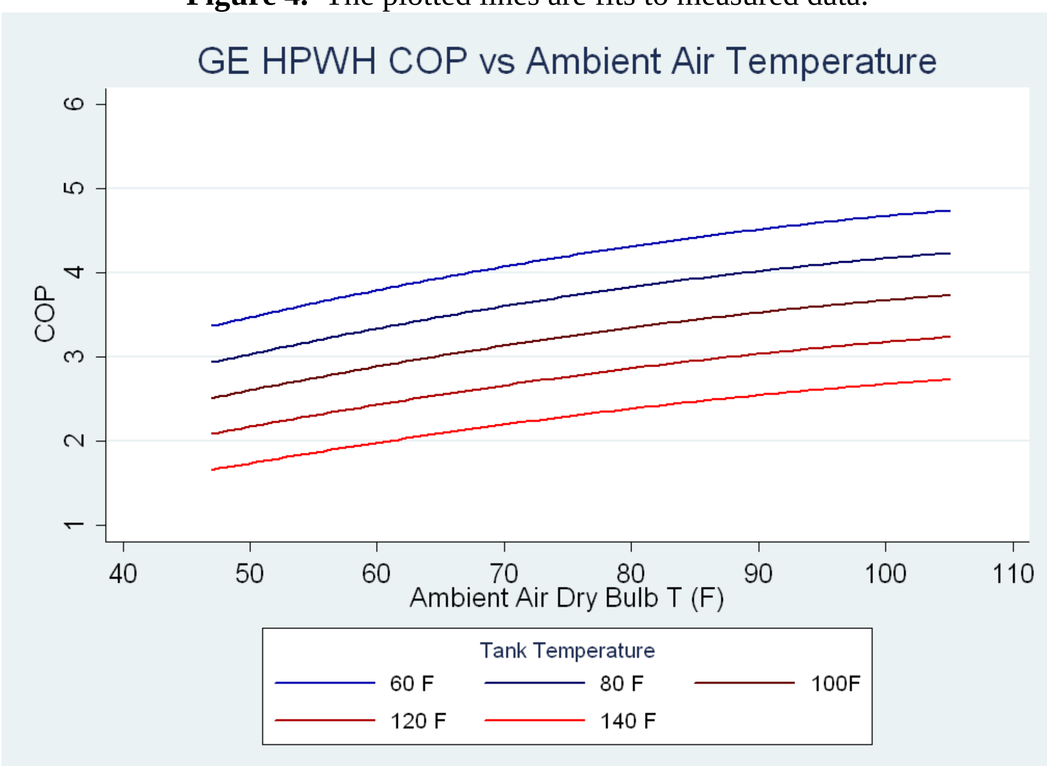


Figure 4. The plotted lines are fits to measured data.



Air Flow Effects on Performance

To evaluate the effect of reduced airflow on the equipment operation, two tests were conducted. The filter area was restricted by 1/3 and 2/3 of its surface area for the measurements. Then, the COP-67 test was carried out. Preliminary analysis shows no discernable impact on performance with either of the blockage amounts. This is important as it implies the system is able to still operate well with dirty and clogged filters up to the restricted amounts tested.

Draw Profile and Capacity

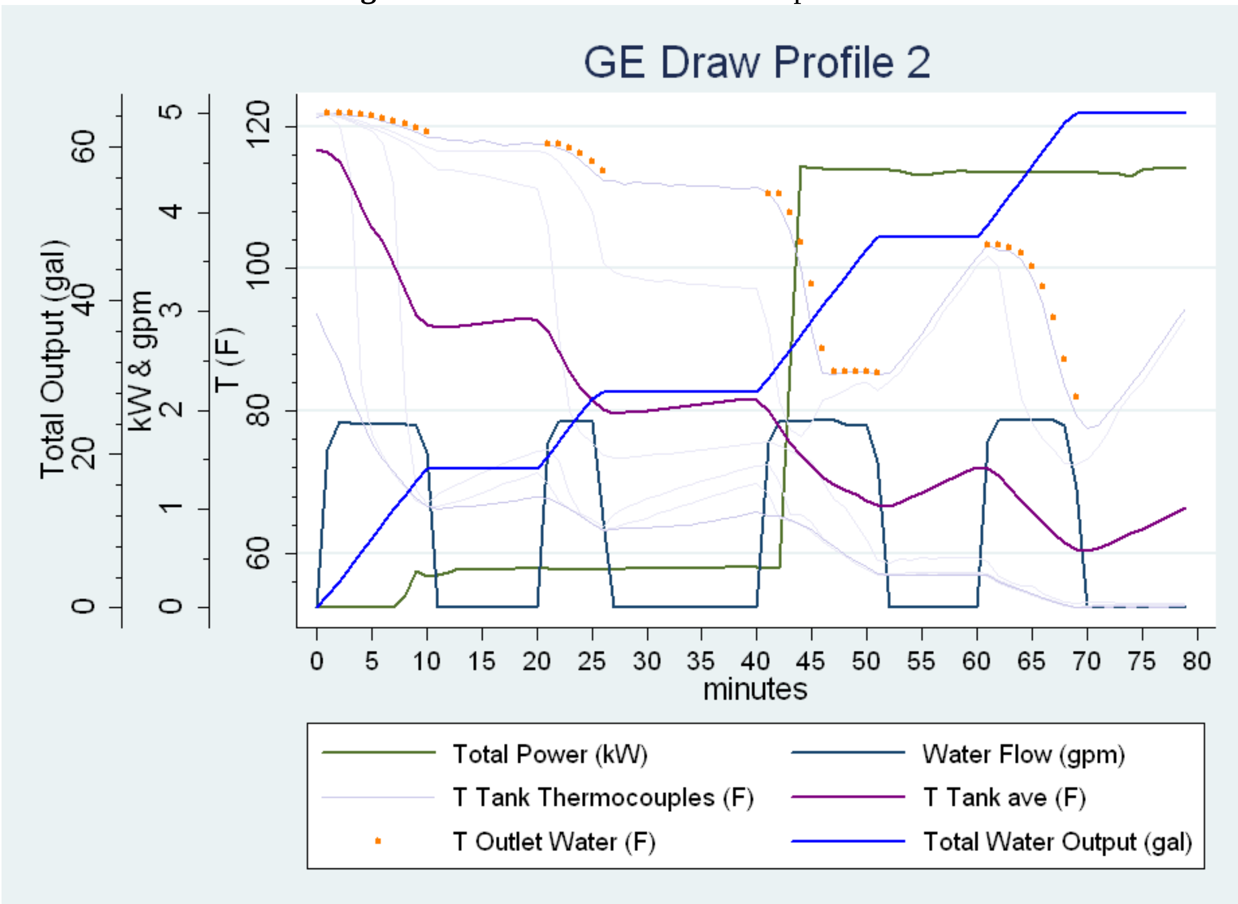
In addition to the standard DOE 24-hr draw profile, two supplemental draw profiles were conducted to observe the water heater under a wider range of potential, real-world, conditions. The first draw profile, referred to as DP-2 in the M&V plan simulated a heavy water use pattern targeting 110 gallons of water per day. The conditions used for DP-2 include: Hybrid mode, 120°F set point, 67.5°F ambient temperature, and 45°F inlet water (to simulate winter seasonal mains temperatures).

Figure 5 shows the first 80 minutes of the test which consist of a total water draw of 60 gallons. The draws simulate four showers occurring during a morning period. The figure shows the tank having enough hot water to complete the first two showers and part of a third. Shortly before minute 10, the compressor turns on (green line ~400W). At minute 43, during the third shower, when the tank temperature has dropped far enough, the compressor turns off and the upper resistance element engages. At the same time, as the draw continues, the outlet water temperature falls below 105°F showing that the tank provides about 40 gallons of useable hot water in a 45 minute period under this scenario. As the draw profile continues, the tank recovers the water temperature to set point using only resistance elements. The draw profile progresses for about 8 more hours beyond the graph in which a night time use pattern is imposed on the tank.

The draw profile demonstrates the important interplay of tank storage, outlet water temperature, and overall efficiency. The tank switches heating devices in an attempt to maintain hot water delivery temperature. As soon as the resistance elements engage, the system efficiency drops from the high heat pump COP greater than 1 to the element COP of 1. One could imagine smaller load scenarios where the elements may not need to turn on whereby maintaining high efficiency levels. Alternatively, a larger tank storage capacity could maintain hot water delivery longer in high demand situations without engaging the resistance elements. Regardless for real-world installations of this equipment, however often the resistance element turns on in a given day, will greatly influence the overall system efficiency.

Lastly, the portion of the draw profile shown in figure 5 is very demanding on the tank. Not surprisingly, the profile shows the water heater lacks enough capacity (both storage and energy output) to meet the load imposed by this test. This finding doesn’t necessarily indicate a shortcoming of the equipment, rather it suggests a larger water heater is the correct size for the load imposed by the test. It is highly unlikely a designer or plumber would choose to install such a small water heater for a high demand application (active family of four).

Figure 5. First 80 minutes of draw profile 2.



Observations on Equipment Design

The last section in the report discusses observations on the equipment design and their implications for operation and performance.

- First, the tank appears to be sized too small in order to take full advantage of the efficiency of heat pump heating. All electric tanks, as compared to gas, have traditionally had lower heating output capacities so are sized larger. Likewise, HPWH heating output, especially at colder temperatures, can be lower still than the resistance elements, suggesting a larger tank is warranted in order to use compressor heating more of the time. This tank, at 45.5 gallons, using its most efficient modes is likely to meet the needs of only light to medium hot water use households. The hot water demands of larger households can be met but they are likely to come at the expense of efficiency. To meet the high demand periods, the water heater will switch back to operating like a resistance element tank. The alternative to not switching to resistance heating is compromised output water delivery temperature. Therefore, for higher water loads, larger tanks are likely to offer the advantage of reduced energy use while maintaining comfort. With more storage capacity, it is likely a tank will be able to heat water more of the time with the heat pump.

- The compressor capacity is also fairly limited. For instance, at 67°F ambient air, heating the tank after a complete draw down (a bath for instance) will take 6-7 hours. A larger compressor would obviously increase heating capacity. The system does appear to be carefully designed, however, because it doesn't enter a defrost mode too frequently. A large compressor has the potential to lower the evaporator coil temperature thus causing coil frosting and forcing the compressor to periodically shut off. Nevertheless, a larger compressor coupled with larger evaporator coils, would increase heating capacity and also system efficiency.

- One way to increase heating capacity while maintaining some level of efficient operation is to remove the compressor-resistance element lockout. Currently, when the resistance element is energized, the compressor shuts off. An improved operational strategy would be to allow both to run simultaneously. For instance, if the total system power draw is limited to 4.5kW, the resistance elements could be decreased in power by 500W (or whatever is necessary to stay underneath the desired draw limit). Under the range of typical conditions, the compressor operates with a COP of 2-4. Therefore, total heating capacity would be 5-6kW, a 10-30% increase. At the same time, overall energy use would drop because the heat pump would operate more of the time. Other scenarios exist where the peak power draw could be designed for other levels (4, 4.5, 5, 5.5kW, etc) depending on utility requirements.

- The control interface on the GE consists of a nice looking LED panel, but changing a set point or changing the operating mode, which are the most basic adjustments a user would make, requires going through several menus. It could be simplified.

- Finally, the equipment operating modes offer a reasonable mix of strategies to meet efficient or high demand scenarios. From an efficiency perspective, one shortcoming is the inability of the compressor to cycle back on in hybrid mode once it has been shut off and the resistance elements take over. An improvement on that strategy would be to have the upper element meet set point in the upper third of the tank and then heat the rest of the tank with the compressor. Not allowing the compressor to turn on again during the recovery cycle is a performance decrement, especially when there are no water draws occurring during that time.